Proton Exchange Membrane Fuel Cell Thermal System Modeling and Control

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***Abstract*—The urgent issue of global warming and its adverse effects, including wildfires, water scarcity, and the spread of diseases, calls for concerted efforts to mitigate emissions and curb climate change. Among the effective strategies is the reduction of carbon emissions, for which hydrogen-powered proton exchange membrane fuel cell systems are vital. These systems generate electricity through chemical reactions involving hydrogen, with only water and heat as byproducts, hence their environmentally friendly nature. Fuel cell efficiency is higher than conventional systems depending on the type and the operating temperature. Proper thermal control is essential for maintaining high efficiency. This research paper aims to examine standard models of proton exchange membrane fuel cell thermal systems and suggest an efficient control approach. The system dynamics are derived from fundamental models, and an adaptive PID controller is simulated with MATLAB/Simulink. The paper also presents a comparative analysis between traditional PID control and adaptive PID, an advanced control technique.**

Keywords—proton exchange membrane fuel cell systems, thermal system modeling and controls, adaptive PID controller, hydrogen-powered system, thermal high-efficiency, thermal control

I. INTRODUCTION

Environmentally friendly energy sources are critical for preserving the environment and dealing with environmental challenges. It is stated that dominating the global energy market with a single energy source is impossible. As a result, the group of various energy source models is shared globally. This has the advantage of allowing different available energy sources to be used [1]. Hydrogen is one of the most abundant elements on the planet, and when hydrogen gas is oxidized, it produces pure water, resulting in no carbon emissions. This makes it appealing for use as an energy source.

The hydrogen-powered proton exchange membrane fuel cell system uses pure hydrogen to generate electrical energy. Hydrocarbon fuels such as natural gas, propane, and methane can also be used in various fuel cell systems. Fuel cell systems are used in multiple applications, including automotive, electronics, aviation, military, and space applications, due to their ease of operation and low operating temperature. Some applications range from portable to large-scale, such as NASA's Apollo project and the space shuttle [2].

Efficiency is one of the relevant aspects of fuel cell systems. It depends on the provided hydrogen, air, and thermal management. Proper temperature, membrane humidity, and the partial pressures of reactants are crucial to avoid stack degradation and for long operation life [3]. The operating temperature affects the polarization curve, so the output voltage.

It is mentioned in [4] that if the entropy changes are minimal, it indicates a stable performance of the fuel-cell system. As thermal management is improved, the density and electricity production also improves, reducing the waste of thermal power. However, with high temperatures, the humidity of the membrane decreases, and as a result, the lifetime of the fuel cell system decreases. Therefore, controlling the fuel cell system's thermodynamics is mandatory to ensure the high performance of the proton exchange membrane.

Two cooling systems are considered: forced convection and free convection. In forced convection, a coolant pump and a radiator circulate the coolant into the system. The free convection system trusts the natural circulation of the coolants. The forced convection system needs a regulator that controls the components in the system. In the literature, there are different types of controllers, e.g., proportional control of the fan speed based on the desired temperature level of the stack [5]; and a feedback PID controller against fast load changes [6]. A novel study presents a variable universe fuzzy PID controller that improves controller performance. An expansion factor adjusts the fuzzy controller and brings better settling time, lower overshoot, and more stable steady-state behavior when compared to the performance of a conventional PID [7]. Another study aims to implement an integral separation of the PID controller for reducing the overshoot under dynamic loads. Only a PD controller is applied when the deviation exceeds a threshold; otherwise, a PID controller is implemented [8]. A large number of studies that concern the thermal management of fuel cell systems are already available.

In this study, an adaptive PID controller is developed to increase the performance of the thermal system under dynamic loads and temperatures. The results of the adaptive PID are compared to those of a conventional PID controller. First, a Proton Exchange Membrane Fuel-Cell (PEMFC) thermal system is modeled and validated. Then the proposed controllers are implemented and tested using MATLAB/Simulink

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simulations. Finally, outcomes are presented based on the simulation result. Section II explains the proton exchange membrane fuel cell thermal system modeling. The mathematical equations are present with the simulation data. Section III shares and explains the validation results of the given model. In section IV, the studied adaptive PID controller structure is presented. Finally, in the V, the simulation results are shown and explained.

II. PEMFC Thermal System Modeling

A. PEMFC Thermal System Overview

The proton exchange membrane fuel cell system is made up of a stack that generates electricity from chemical reactions, an anode path that is in charge of the fuel supply, a cathode path that is in control of the air supply, and a thermal path that is in charge of cooling/warming the stack. The diagram that represents the PEMFC thermal system is depicted in Fig. 1.

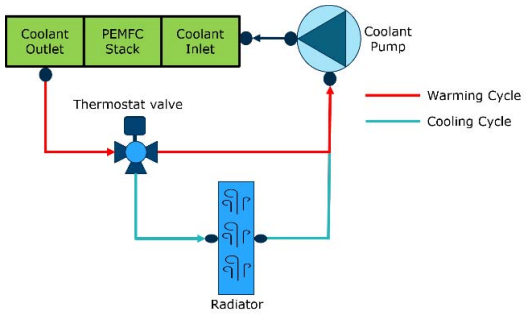

Fig. 1. PEMFC thermal system diagram.

The stack that generates heat, the coolant pump that pumps the coolant and maintains a proper temperature difference between the stack inlet and outlet, the thermostat valve that allows switching between system warming and cooling, and the radiator that cools the coolant in the system are the main components of the thermal system.

The thermostat valve separates the thermal path into warming and cooling cycles. The warming cycle raises the operating temperature by turning off the thermostat valve and bypassing the radiator. To cool down the coolant, the thermostat valve is open, and the radiator will reduce the temperature of the coolant with air. The blown air volume is proportional to the degree of radiator opening. A greater opening degree means greater heat dissipation. The rotational speed of the coolant pump is proportional to the coolant flow rate. A higher flow rate means more heat dissipation from the stack. The electrical efficiency of a proton exchange membrane fuel cell (PEMFC) typically ranges between 40% and 60%, depending on factors such as operating temperature, cell size, and reactant pressure. For the purposes of this study, electrical efficiency is assumed to be set as 55% to simplify the modeling process. Stack humidity is regulated within the air path using a humidifier and bypass valve. It is presumed that the humidity of the reactants is maintained at an optimal level, as the focus of this research is on the coolant path and the proposed controller is designed to be robust against disturbances arising from the air path.

B. Stack Modeling

The stack is a crucial component of a fuel cell system as it is where the chemical reaction takes place. During operation, the stack only generates heat and water as waste products. The amount of waste power, or generated thermal power, is determined by the stack's voltage, current, number of cells, and efficiency, and can be calculated using the following formula:

$$Q_{StackHeat} = U_{Stack}\, I_{Cell}\, \mathrm{N}_{cell}\, \eta_{StackTherm} \tag{1}$$

where $Q_{StackHeat}$ is the heat generated by stack, U_{Stack} is the stack voltage, I_{Cell} is the single cell current, N_{cell} is the total cell number, and $\eta_{StackTherm}$ is the thermal efficiency of the fuel cell. The generated heat must equal the dissipated heat to maintain a constant operating temperature. The only heat dissipation assumed in this study is heat exchange with the coolant and heat radiation toward the environment.

To simplify the model, the water vapor heat exchange is ignored because its effect is minor. The heat dissipated by coolant is as follows:

$$Q_{Coolt} = \dot{m}_{Coolt} C_{Coolt} Tdif_{Stack} \tag{2}$$

where Q_{Coolt} is the heat dissipated by coolant, $\dot{m}_{Coolt}$ is the coolant flow rate, C_{coolt} is the heat capacity of the coolant, and $Tdif_{Stack}$ is the temperature difference between the stack outlet and the stack inlet. The temperature changes in the stack are caused by the difference between the generated and the dissipated heat, which is defined using the following:

$$\Delta T_{Stack} = \int \frac{(Q_{StackHeat} - Q_{Coolt})}{C_{Stack} M_{Stack}} dt \tag{3}$$

where ΔT_{Stack} is the stack temperature change, C_{Stack} is the stack heat capacity, and M_{Stack} is the stack mass.

TABLE I. PEMFC Stack Parameters

Stack parameter	Value	Unit
Stack cell number (N_{cell})	432	-
PEMFC thermal efficiency ($\eta_{StackTherm}$)	45	%
Stack heat capacity (C_{Stack})	500	$\frac{J}{kgK}$
Stack mass (M_{Stack})	31	kg

C. Radiator Modeling

A radiator is a heat exchanger that uses air to reduce the temperature of the coolant from the stack. The coolant flows through the stack, dissipating heat and preventing overheating. The coolant is then routed to the radiator to be cooled by air. Water-cooled radiators, air-cooled radiators, oil-cooled radiators, and other options are available. The coolant in this study is cooled using air. The amount of heat dissipated is proportional to the radiator's opening degree. As a function of the opening degree, the air mass flow can be calculated as follows:

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$$\dot{m}_{Air} = 1.6160\ \vartheta_{Radr} + 0.3192 \quad (4)$$

where $\dot{m}_{Air}$ is the air mass flow through the radiator, and ϑ_{Radr} is the opening degree of the radiator. It is also necessary to include a condition during modeling stating that if the radiator is fully closed, the air mass flow must equal 0 kg/s.

The dissipated heat by conduction of the radiator can be found as follows:

$$h_{Radr} = 71.74\ \dot{m}_{Air}^2 + 71.74\ \dot{m}_{Air} + 4.033 \quad (5)$$

where h_{Radr} is the heat conduction of the radiator.

Finally, the heat dissipated by convection in the radiator is defined using:

$$Q_{Radr} = h_{Radr}\ A_{Radr}\ Tdif_{RadrAmb} \quad (6)$$

where Q_{Radr} is the heat dissipated by the radiator, A_{Radr} is the effective radiator area, and $Tdif_{RadrAmb}$ is the temperature difference between the radiator and the ambient. The radiator's effective area is assumed to be $A_{Radr} = 0.3\ m^2$.

D. Coolant Pump Modeling

As previously stated, two types of cooling systems are forced convection and free convection. The coolant pump is the primary component of this forced convection cooling system. A coolant pump is a pump that moves the coolant in the thermal system to circulate. With proper control, it keeps the temperature difference between the stack inlet and outlet at the desired level. To simplify the modeling process, the coolant mass flow rate is represented as a 1D look-up table that takes the coolant pump rotational speed as input.

$$\dot{m}_{Coolt} = f(\Omega_{CooltPmp}) \quad (7)$$

Here, $\dot{m}_{Coolt}$ represents the coolant's mass flow rate as a function of $\Omega_{CooltPmp}$ the pump rotational speed. Pump rotational speed is saturated between 100 and 6000 rpm.

E. Thermostat Valve Modeling

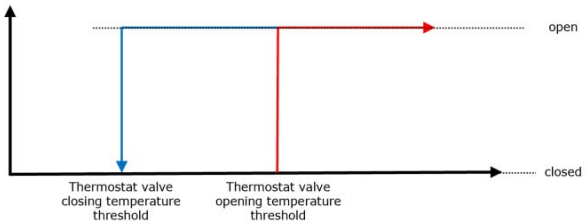

Fig. 2. Thermostat valve behavior.

A thermostat valve, or the three–way valve, controls the coolant flow circulation cycle, warming cycle, or cooling cycle. To warm up the stack, a warming cycle is implemented to bypass the radiator at the beginning of fuel cell operation. After a specified operational temperature is reached, the thermostat valve activates the cooling cycle, allowing the radiator to be controlled and the coolant to be cooled. Thermostat valve behavior is represented by a hysteresis function, as depicted in Fig. 2.

F. Stack Inlet Temperature Evaluation

The thermostat valve status determines the temperature at the stack inlet. If the thermostat valve is open or the cooling cycle is on, the stack inlet temperature equals the radiator outlet temperature. Otherwise, the temperature at the stack input and outflow is the same. A rate limiter is used to simulate the behavior of temperature dynamics.

G. Stack Outlet Temperature Evaluation

The stack outlet temperature always starts from the stack inlet temperature, and based on internal temperature change, it cools down or warms up. The stack outlet temperature can be written as follows:

$$T_{StackOut} = T_{StackIn} + \int \Delta T_{Stack}\ dt \quad (8)$$

where $T_{StackOut}$ is the stack outlet temperature, $T_{StackIn}$ is the stack inlet temperature, and ΔT_{Stack} is the stack's internal temperature change.

H. Radiator Inlet and Outlet Temperature Evaluation

The radiator inlet temperature equals the stack outlet temperature, while the radiator outlet temperature is calculated based on the radiator inlet temperature and heat dissipated by the radiator. The radiator inlet temperature T_{RadrIn} is set as an initial value. The radiator's temperature change ΔT_{Radr} can be calculated using (9):

$$\Delta T_{Radr} = \frac{Q_{Radr}}{\dot{m}_{Coolt}\ C_{Coolt}} \quad (9)$$

where C_{Coolt} is the coolant heat capacity. The coolant heat capacity is assumed to be $C_{Coolt} = 4200 \frac{\text{J}}{\text{kg}}\text{K}$. Using the (10), the radiator outlet temperature $T_{RadrOut}$ can be obtained:

$$T_{RadrOut} = T_{RadrIn} + \int \Delta T_{Stack} - \Delta T_{Radr}\ dt \quad (10)$$

III. Model Validation

Simulation and model calibration are necessary to ensure a realistic representation of the system. To achieve this, the proposed model is simulated under various loads while maintaining fixed controller outputs. In the first simulation, only the thermostat valve control is activated. Simulation parameters are given in Table II. In Fig. 3 and Fig. 4, the radiator is bypassed until the stack inlet temperature reaches the thermostat's open threshold temperature. When the stack inlet temperature reaches the target, the radiator is activated, and the stack cools down towards the thermostat close to the threshold temperature. Since the radiator and the coolant pump are operated at a fixed level, keeping the temperature at the desired level is impossible. It is

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also shown that the stack outlet temperature follows the stack inlet temperature with a certain temperature difference thanks to the coolant pump.

TABLE II. 1ST VALIDATION TEST PARAMETERS

System Parameters	Value	Unit
Coolant pump speed	3000	rpm
Radiator opening degree	50	%
Thermostat valve close temperature limit	72	$°C$
Thermostat valve open temperature limit	78	$°C$
Stack cell voltage	700	mV
Stack current	300	A
Simulation time	120	s

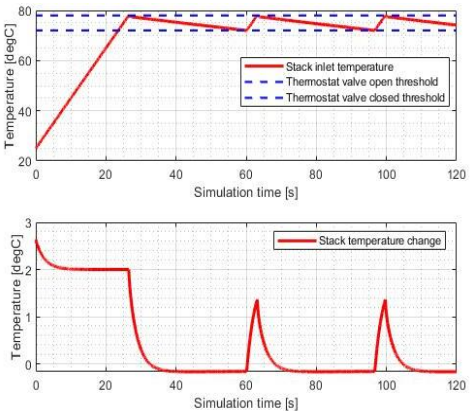

Fig. 3. 1st validation results 1: (a) Stack inlet temperature and (b) Stack temperature change.

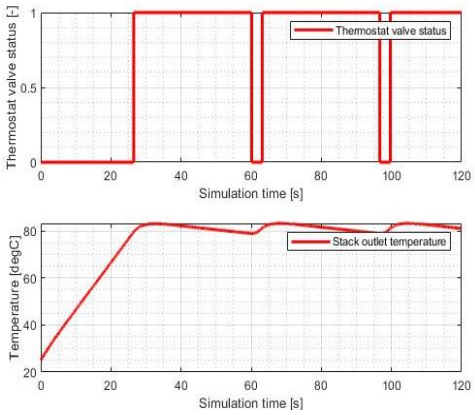

Fig. 4. 1st validation results 2: (a) Thermostat valve status and (b) stack outlet temperature.

The system was then simulated under dynamic load, using the same in Table II. As can be seen from Fig. 5 and Fig. 6, the stack inlet temperature is not affected by the stack current, but the output is affected, especially high load changes between 180th second and 220th second. As shown in Fig. 7 (a) and Fig. 7 (b), if the system is operated with a low coolant pump speed, it is not enough to keep the stack inlet outlet temperature difference steady. This also shows the necessity of the proper controller that controls the thermal system. In summary, the overall model represents the behavior of the fuel cell thermal operations well.

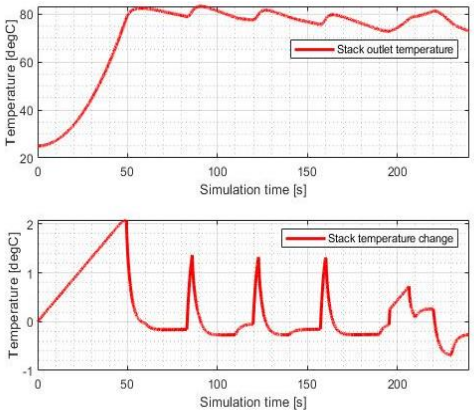

Fig. 5. 2nd validation results 1: (a) Stack outlet temperature and (b) stack temperature change.

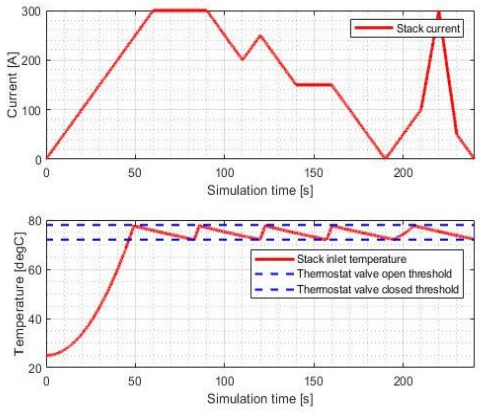

Fig. 6. 2nd validation results 2: (a) current and (b) inlet temperature.

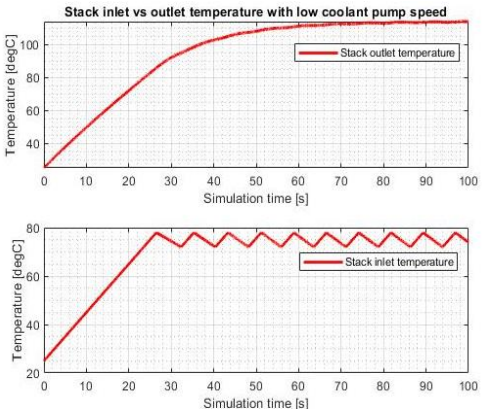

Fig. 7. Low coolant pump speed effect: (a) Stack outlet temperature and (b) stack inlet temperature.

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IV. PEMFC Thermal Control

A. PEMFC Thermal Control Overview

A suitable controller is required for forced convection cooling systems to regulate the thermostat valve, radiator, and coolant pump. Different types of controllers, such as proportional controllers, feedback PID controllers, fuzzy PID controllers, integral separation PID controllers, etc., are discussed in the literature. There are benefits and drawbacks to each. Fuzzy logic controllers, for instance, offer excellent precision and are a straightforward choice for nonlinear and complex systems. However, accurate fuzzy logic controllers require more fuzzy grades, which could lead to the rule's exponential growth.

This study makes use of model reference adaptive control (MRAC). An adaptive PID controller, also known as a self-tuning controller, regulates coolant pump speed to improve thermal management performance under varying loads and temperatures. The temperature difference between the stack inlet and outflow must be maintained, together with the stack inlet temperature. This also brings benefits under varying environmental conditions and system disturbances. The results of this design are compared to the results of a conventional PID controller. The general structure of the adaptive PID controller can be seen in Fig. 8.

Table III depicts some of the used structure inputs and outputs.

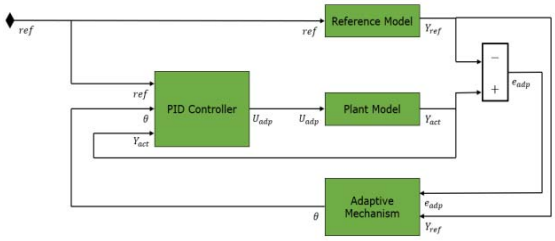

Fig. 8. General adaptive PID structure.

TABLE III. General Adaptive PID Structure Symbol Descriptions

Symbol	Description
ref	desired system output
Y_{ref}:	reference model output
Y_{act}	actual system output
e_{adp}:	adaptive mechanism error
θ	adaptation factor
U_{adp}	adaptive PID controller output

The plant model described in Section II is used in the system design. The system provides overall stability and durability with a traditional PID and PI controllers. The reference model depicts the desired closed-loop system behavior. Generally, the system's response is intended to follow the reference. Therefore, a fundamental transfer function in conjunction with a fine-tuned PID controller can achieve that goal. Fig. 9 displays the reference model that was provided. The tuning is done via the MATLAB PID tuner tool, and the PID controller gains and performance criteria can be found in Table IV.

TABLE IV. PID Controller Gains and Performance Criteria

Parameter	Value
P	1.65
I	1.02
D	0.65
Rise time	1.28 seconds
Settling time	5.94 seconds
Overshoot	1.55 %

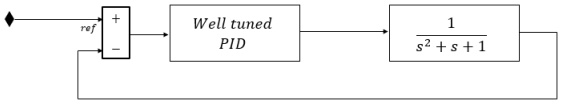

Fig. 9. Reference model structure.

The adaptive mechanism is this structure's most crucial component. The adaptive mechanism automatically modifies the controller output based on the reference model and the tracking error difference between the reference model's output and the plant model's output. Here, the goal is to make the plant model output follow that of the reference model, meaning that the tracking error is zero. Fig. 10 depicts the structure of the adaptive mechanism.

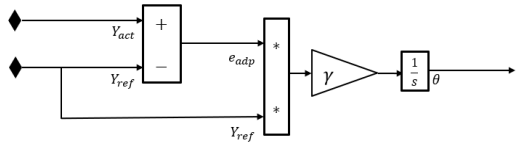

Fig. 10. Adaptive mechanism.

It can be represented as the following formula:

$$\theta = \int \gamma((Y_{act} - Y_{ref})Y_{ref})dt \tag{11}$$

where θ is the adaptation factor, γ is the learning rate, Y_{act} is the actual model output, Y_{ref} is the reference model output. The higher learning rate adapts the plant model changes faster, but it is very sensitive to environmental disturbances and varying setpoints. That brings a risk of the unstability of the system. Therefore, there is a tradeoff in choosing the learning rate. It is not always good to use a higher learning rate value. Adverse effects should be considered while choosing the learning rate.

B. Radiator Control

The radiator reduced the coolant temperature by using air. A conventional PI controls the stack inlet temperature, and the desired stack inlet temperature is given as a reference. The

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controller output is saturated between 0 – 1, in which 0 corresponds to 0% and 1 corresponds to 100%.

C. Coolant Pump Controls

The coolant pump is used to force the coolant into the thermal system. It controls the temperature difference between the stack inlet and outlet. An adaptive PID controller is developed as mentioned in the section "IV. A PEMFC Thermal Control Overview", to control the pump. The desired temperature difference between the stack inlet and outlet is given as a reference to the controller. The controller output is saturated between 0 – 6000, while the physical limit of the modeled pump is saturated between 100 – 6000 rpm. Adaptation factor (θ) is chosen 0.01.

D. Thermostat Valve Controls

The thermostat valve is used to control the coolant flow direction. The warming cycle is activated to warm up the stack, and the cooling cycle is activated to cool down the stack. To control the thermostat valve, an on–off controller is developed. It monitors the stack inlet temperature and activates the cooling cycle or deactivates it based on its value. A gap exists between opening and closing temperature thresholds to keep the system stable. Otherwise, there would be some oscillations at the temperature threshold.

E. Tuning PID Gains

The adaptive PID controller is also referred to as a self-tuning PID controller, which does not require highly precise tuning. Instead, trial-and-error tuning can be used to adjust the PID controller gains and maintain system stability. This method is faster and simpler, leading to reasonable results.

V. Simulation Results

A. Thermal Controls under Static Loads

The complete system is tested under static load with a static operation temperature point. The coolant pump PID controller is tuned well enough to keep the system stable because it is expected from the adaptive mechanism to tune PID gains. However, as the simulation is not performed under dynamic conditions, the effect of the adaptive mechanism cannot be observed. Thus, the adaptive mechanism is disabled. Simulation parameters can be seen in Table V.

TABLE V. Static Load and Setpoint Simulation Parameters

Name	Value	Unit
Stack inlet temperature setpoint	75	$°C$
Stack inlet outlet temperature difference setpoint	5	$°C$
Thermostat valve close temperature limit	72	$°C$
Thermostat valve open temperature limit	78	$°C$
Stack cell voltage	700	mV
Stack current	300	A
Simulation time	60	s

Fig. 11(a, b) and Fig. 12 indicate proper functioning of the coolant pump and radiator under static loads without the adaptive mechanism. Inlet and outlet temperatures remain equal until reaching the desired operating temperature.

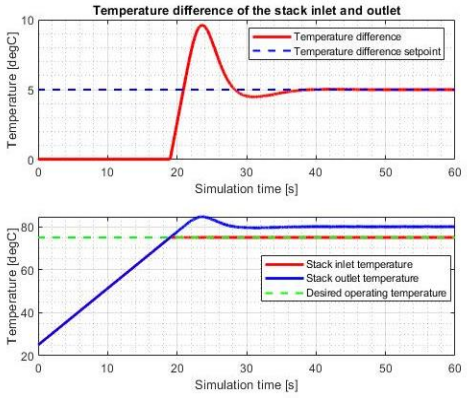

Fig. 11. Simulation results under static load, temperature diff control, PID: (a) Stack temperature difference and setpoint (b) stack inlet, outlet, and the desired operating temperature.

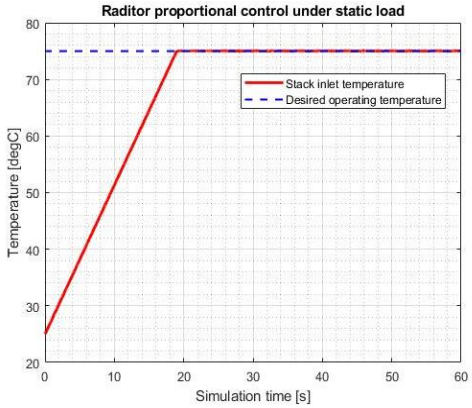

Fig. 12. Radiator PI control result under static load.

B. Thermal Controls under Dynamic Loads

Fuel cell systems are typically driven under dynamic loads, mainly when used as a booster. This simulation makes use of the driveline load map shown in Fig. 13. Fig. 14 depicts the conventional PID response under dynamic loads. Adaptation factor (θ) is chosen 0.01. Fig. 14 (a) illustrates the stack's inlet and outlet temperature difference when tracking a given set point, while Fig. 14 (b) depicts the stack's inlet and outlet response.

Fig. 15 (a) and Fig. 15 (b) show the system under the same conditions but with the coolant pump adaptive PID controller. The coolant pump regulates the temperature difference towards the reference when the adaptive mechanism is engaged. Because of the inertia of the temperature dynamics, it introduces some oscillation at the start. The adaptive PID controller performed noticeably better than the classical PID with experimental tuning. The IAE stands for Index Measures Performance and is used as a performance measure to evaluate the proposed controllers. The

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IAE of the adaptive PID controller is 267.8, while the IAE of the conventional PID is 325.3. The adaptive PID controller improves the system response by 17.67%. Fig. 16 depicts the changes in the adaptation factor (θ) during operation.

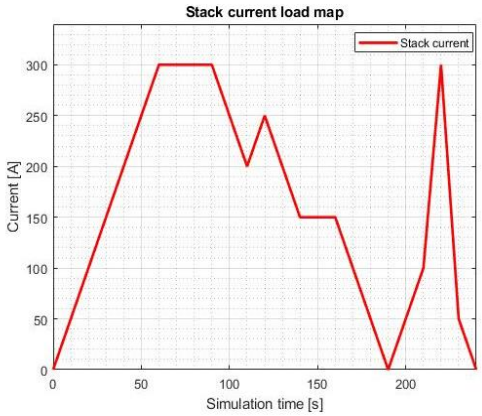

Fig. 13. Stack current load map.

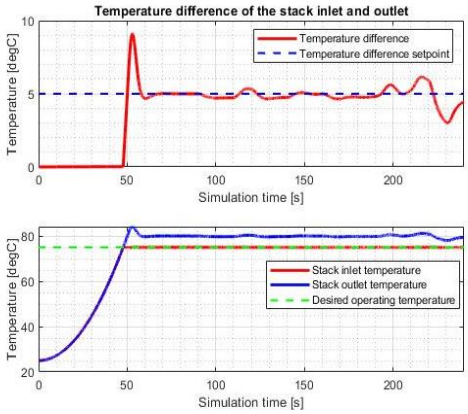

Fig. 14. Simulation results under dynamic loads, temperature diff control, PID: (a) Temperature difference setpoint and actual values (b) stack inlet, outlet, and the desired operating temperature.

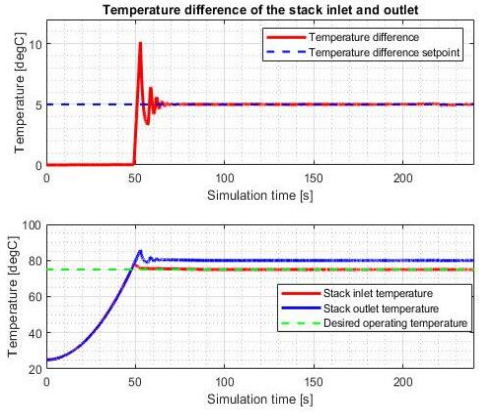

Fig. 15. Simulation result under dynamic loads, temperature diff control, adaptive PID: (a) Temperature difference setpoint and actual values and (b) stack inlet, outlet, and the desired operating temperature.

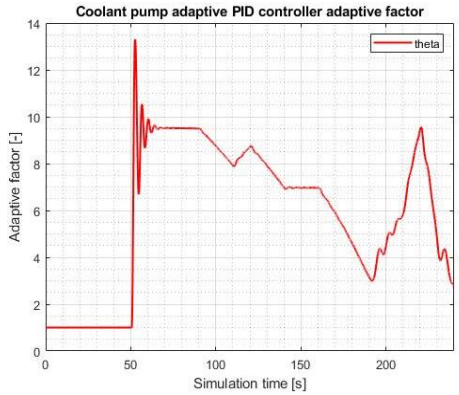

Fig. 16. Coolant pump adaptive PID controller adaptation factor under dynamic loads.

C. *Thermal Controls under Dynamics Loads and Dynamic Temperature Setpoints*

The efficiency of the fuel cell system is affected by temperature, and the ideal temperature for optimal performance varies based on the amount of load on the system. The researchers tested their proposed system under varying loads and set point levels are presented in Fig. 17 and Fig. 18. Adaptation factor (θ) is chosen 1.

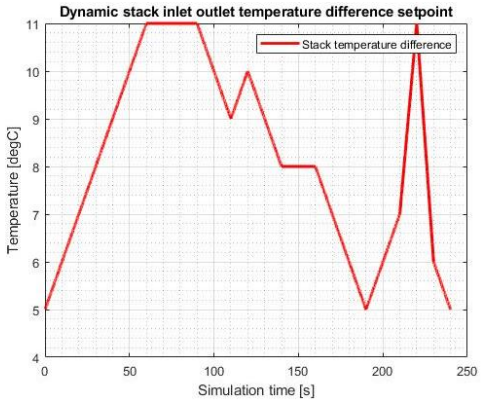

Fig. 17. Dynamic stack temperature difference setpoint.

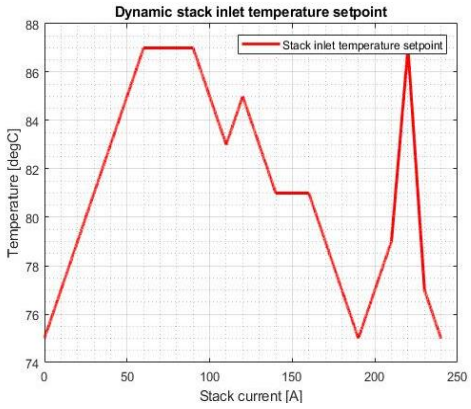

Fig. 18. Dynamic stack inlet temperature setpoint.

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The complete system is tested with the conventional PID controller, and the system's response is shown in Fig. 19. The IAE index is 477.9 for this controller.

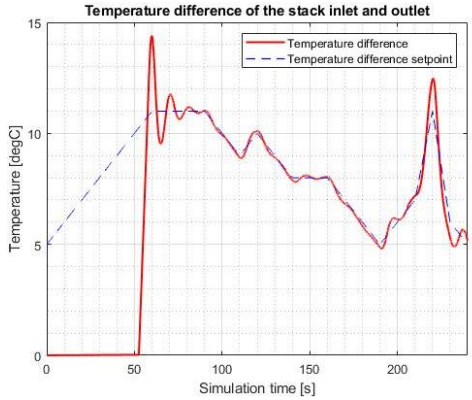

Fig. 19. PID controller result with the dynamic temperature diff setpoint.

When the adaptive mechanism is turned on, fluctuations occur before the system reaches the desired set point. As a result, the IAE index goes up to 830.1. This is worse than the performance of the designed PID controller. The temperature response of the system with the adaptive PID controller is shown in Fig. 20.

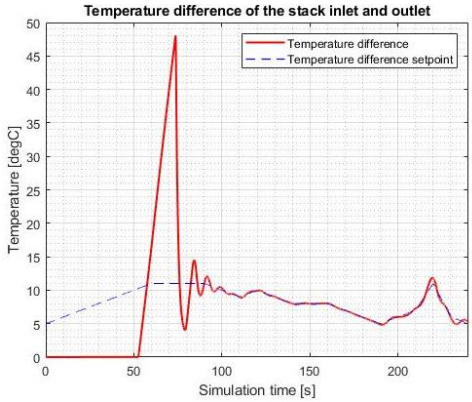

Fig. 20. Adaptive PID controller result with the dynamic temperature diff setpoint before adjustment.

Fig. 21 displays the variation in the adaptation factor and the time taken to reach the desired temperature. As previously stated, the inlet and outlet temperatures of the stack are identical until the desired operating temperature is attained. Nonetheless, during this period, the adaptive mechanism is triggered and integrates the error between the reference model's desired output and the actual output, resulting in a negative adaptation factor. As a result, the minimum adaptive mechanism factor is established at one until the desired stack inlet temperature is achieved. Before attaining the desired stack inlet temperature, the adaptive PID behaves similarly to a traditional PID controller. Fig. 22 demonstrates the outcomes of the adaptive PID controller for the adjusted dynamic temperature differential set point.

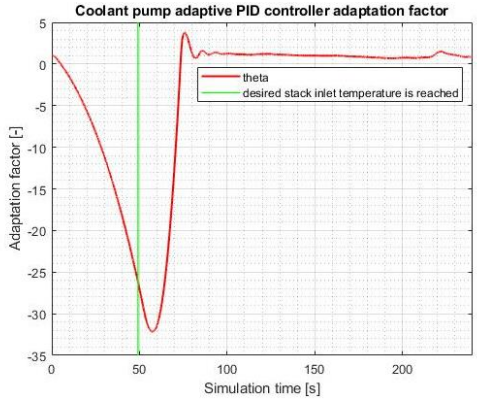

Fig. 21. Adaptive mechanism adaptation factor.

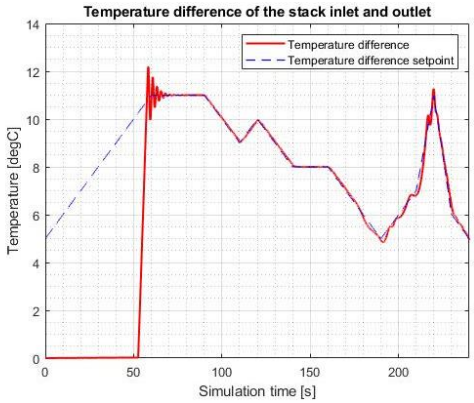

Fig. 22. Adaptive PID controller result with the dynamic temperature diff setpoint, after adjustment.

The IAE index is 445.43, which means the adjustment enhances 46.3% controller performance. And it is also enhanced by 6.79% controller performance compared with the conventional PID controller. The controller output remains unsaturated during simulation, thanks to the well-designed adaptive PID controller.

VI. Conclusions

Simulation modeling is a powerful tool for solving real-world problems in a safe and efficient manner and provides low-cost yet valuable solutions by offering clear insights into complex systems across various industries and disciplines. Among the most significant technologies that simulation modeling can be applied to is the hydrogen-powered proton exchange membrane fuel cell system (PEMFC), which plays a crucial role in reducing carbon emissions. This system generates electrical energy through chemical reactions involving hydrogen. Efficiency is a key consideration in all systems, including PEMFC, and has been a topic of particular importance. This research study presents a model of the thermal system of a fuel cell, including the coolant pump, radiator, thermostat valve, and stack. The plant model is tested under different conditions, such as dynamic loads, and low coolant pump speed, to realize the actual system behavior. Simulation results show that the

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modeled plant reflects the behavior of the fuel cell thermal dynamics properly.

A proper controller is one of the key aspects to operating the systems are the optimum points. As expected, fuel cell systems work under varying loads and optimum operating points. Therefore, controller adaptation is also crucial. To achieve this target, a model reference adaptive PID controller is developed and tested under varying conditions. The results analysis indicates that the self-tuning mechanism of the adaptive PID controller provides better control performance against dynamic loads and target changes compared to the conventional PID controller. As a performance measure, the IAE method is used.

As future work, a heat exchanger may be considered in the system to perform freeze startup. Temperature-dependent stack polarization curves and efficiency maps may be incorporated to achieve a more realistic representation of the system's behavior. Other adaptive mechanisms, such as PID gain adaptation, may also be explored, and stability analysis could be performed to ensure the robustness of the system.

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